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ADVANCED POWER PLANTS FOR USE WITH HOT DRY ROCK (HDR) AND ENHANCED GEOTHERMAL TECHNOLOGY

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1. ABSTRACT

The future commercialization of the Hot Dry Rock (HDR) or Enhanced Geothermal System (EGS) technologies will be dependent on solving both technical and economic issues. The major identified barriers to commercialization of these technologies are the costs of drilling the wells, the supply of water and the pumping of the HDR produced brine. Drilling costs are related to the geological formations and well depth, and thus power plants, which effectively utilize lower temperature fluids from shallower wells can reduce power production costs. Power plants which do not consume any water in the conversion process regardless of fluid temperatures, and are insensitive to water chemistry, can optimize HDR/EGS commercial power projects. Organic Rankine Cycle (ORC) binary based power conversion technology effectively utilizes air cooled condensers with no consumption of geothermal fluid. Such closed loop power plants generate electricity with EGS produced fluid with temperatures from 95^{o}C to 315^{o}C without loss of water in the power plant, and with no corrosion or scaling of the plant components. In addition, modular power units may be used to increase power plant capacity as more EGS fluid production is developed. This presentation describes advanced geothermal power conversion systems and along with case histories of operating power plants employing these conversion systems.

2. BACKGROUND

The greatest potential for the utilization of geothermal energy to generate electrical power may well be in the utilization of heat from geological formations that lack natural water. This heat utilization process is known as Hot Dry Rock (HDR) technology, also referred to as Enhanced Geothermal Systems (EGS) technology. As HDR geothermal technology advances, a significant portion of the world's needs may be met from the widely distributed HDR resources.

The costs of drilling injection and production wells and the pumping and supply of water are currently the major cost barriers to commercializing HDR/EGS technology. With drilling costs related both to the geological formations and to well depth, power plants which can effectively make use of lower temperature fluids from shallower wells will reduce power production costs and overcome these barriers.

Power plants which do not consume any water, regardless of HDR fluid temperatures, and which are insensitive to water chemistry, will be the most desirable for HDR/EGS applications, since even the anticipated loss of 5 to 10% of the water injected into the geological structure of an HDR system imposes a serious requirement for make up water.

The field proven (over 600 MW) advanced ORMAT ORC technology power plants will optimize the effectiveness of future HDR/EGS systems over the widest range of fluid temperatures and characteristics.

3. ORC BASED POWER CONVERSION TECHNOLOGIES

3.1 Modular Binary Power Plants

ORC technology, as incorporated into the ORMAT® Energy Converter or OEC, allows for the effective utilization of air cooled condensers in power plant applications with geothermal fluid temperatures to 315^{o}C. The basic OEC geothermal air cooled binary power plant cycle is shown schematically in Figure 1. In this cycle the geothermal fluid heats the organic motive fluid in the vaporizer, usually a tube and shell heat exchanger, with the geothermal fluid flowing in the tubes and the motive fluid in the shell side.

The vaporized motive fluid, typically iso-pentane, drives a turbine which is direct coupled to the generator. Grid compatible power is generated and fed to the plant sub-station. The spent motive fluid vapors leave the turbine at a positive pressure, above one bara, are condensed in the finned tube air cooled condenser and pumped back into the vaporizer to repeat the cycle. No geothermal or HDR/EGS produced fluid is consumed or lost in the plant, and 100% of the fluids are injected.

The basic binary cycle is generally most effective when used with geothermal, or HDR fluids, below 176^{o}C. The binary power system operates with the produced fluid continuously under the high pressure, with the fluid is in contact only with the power plant piping and the heat exchanger tubes. Thus, except for the losses in the geological structure, there is no loss of water circulating in the power conversion system. With the entire system under pressure, there is no corrosion or scaling in the power plant or well bore. Typically the HDR/EGS injection wellhead pressures are expected to be in the range of 100kg/cm^2 during operating flow conditions, with production wellhead pressures in ranging to 15kg/cm^2, (within the normal range of 7 to 20kg/cm^2 for binary power plant systems).

The use of modular power units allows for increasing the plant size as the HDR/EGS fluid production capability is increased. For HDR systems where the geological structure can produce fluids at the surface at temperatures above 176^{o}C, it is usually more effective to flash a portion of the produced fluid into steam and use geothermal combined cycle technology

3.2 Geothermal Advanced Technology Power Plants

The geothermal combined cycle power technology accommodates lower pressure flashed steam, at pressures as low as 1.2 bara, as well as higher pressure steam, at pressures up to 100 bara.

Two Phase Binary Cycle

For lower pressure steam, depending on the steam wetness and characteristics, the two phase binary cycle, as shown in Figure 2, may be employed. In the two-phase binary system the low pressure steam from the flash tank is condensed in the vaporizer of the binary system, and the hot brine is used to preheat the organic motive fluid.

As in the basic binary system the motive fluid vapors drive the turbine, and are condensed in the air-cooled condenser. The use of air-cooled condensers with organic motive fluid vapors is more effective than with steam under vacuum, as in condensing steam turbines, because the condensing organic motive fluid vapors, which are under positive pressure, have a much smaller volume than the low pressure steam during the condensing cycle. As a result the piping and heat transfer surfaces for the organic vapors are much smaller than would be required for air-cooled steam condensers.

Geothermal Combined Cycle

With high pressure flashed steam the ORMAT® Combined Cycle Unit (OCCU), as shown in Figure 3, is employed. In this system the high-pressure steam drives the back-pressure steam turbine, identified as Turbine Level I. The low pressure steam from Level I is condensed in the vaporizer of a binary system, with the resulting motive fluid vapors driving the binary Turbine Level II. The brine remaining in the steam separator tank may be used in a separate binary cycle to generate additional power.

4. CASE HISTORIES OF ADVANCED TECHNOLOGY POWER PLANTS

4.1 Binary Power Plants

Nagqu Geothermal Power Plant, Tibet, P R of China

The Nagqu geothermal power plant, located 200 kilometers north of Lhasa, Tibet, is the highest geothermal plant in the world at 4,500 meters ASL. The project is owned and operated by the Nagqu Power Bureau and provides power to a local mini-grid. It includes two production wells and one 1.3 MW air cooled OEC modular binary power plant, installed and commissioned in 1993 (see Figure 4). The wells are pumped and produce 4,200 liters per minute of geothermal fluid at 110°C. The plant initially operated for 6,400 hours and was shut down following failures of the down-hole pumps. The wells were temporarily operated without the pumps and the subsequent scaling resulted in the plant being shut down. The down hole pumps were replaced and the plant has been operating properly since August 1998.

Bay of Plenty Geothermal Power Plants, Kawerau, New Zealand

The Kawerau geothermal field has a total tested capacity of 200MW_e, and 31 drilled wells, with a maximum depth of 1611 meters and a maximum bottom hole temperature of 310°C. The New Zealand Ministry of Energy sold geothermal process steam to Tasman Pulp and Paper, with the process surface discharging the 174°C separated brine both as steam into the atmosphere and brine into the Tarawera River. Bay of Plenty Electric obtained the rights to the spent geothermal fluid and installed two 1.3 MW air cooled modular binary OEC units in 1989 and one 3.8 MW air cooled modular binary OEC in 1993, for a total of 6.4 MW capacity. See Figure 5 for a photograph of the 3.8 MW unit.

These modular power units utilize the 174°C brine, cooling it to 110°C, in the first two 1.3 MW units, and to 80°C in the 3.5 MW unit. The electricity generated from a total flow of some 550 tons/hr of geothermal fluid, is 7.1 MW. After 10 years of continuous operation the Kawerau Geothermal Power Plants are operating at over 98% availability.

4.2 Two Phase Steam/Binary Combined Cycle Power Plant

São Miguel, Geothermal Power Plant, Azores, Portugal

The privately owned São Miguel power plant, which consists of two dual air cooled OEC modules commissioned in 1994 and two dual modules commissioned in late 1998, generates 14 MW which is sold to Electricity of the Azores, Ltd. This project utilizes 128 t/h of 5.1 bara steam and 412 t/h of 153°C geothermal fluid. (See Figure 6).

The two phase flow is used in a modular binary system, which also makes use of the steam condensate to dilute the injected brine so as to lower the injection temperature and thus extract more heat from the produced geothermal fluids. The first phase plant operated continuously, with an availability factor of 98%. Air-cooling and 100% injection of all geothermal fluids and gases has resulted in a very low environmental impact. With the development of additional production wells the construction of the second 9 MW phase, bringing the total generation capacity to 14 MW, was completed in late 1998.

4.3 Integrated Geothermal Combined Cycle Power Plant

Rotokawa Geothermal Power Plant, Rotokawa, New Zealand

The Rotokawa power plant, which is owned by Rotokawa Generation Ltd., a Maori Trust corporation, is an integrated geothermal combined cycle plant comprised of one 25 MW (gross) ORMAT® Combined Cycle Unit (OCCU) and one 5 MW binary OEC Module, for a total 30 MW installed capacity. The power plant was constructed and commissioned 1997, and utilizes wells drilled by the Maori Trust. (See Figure 7).

The ORMAT® Combined Cycle Unit (OCCU) utilizes 304 t/h of steam at an inlet pressure of 23.2 bara with the steam from the Level I back pressure turbine exiting at 1.3 bara. The net power produced by the OCCU is 23.5 MW. The OEC modular binary unit utilizes 304 t/h of 219°C brine, with a high content of corrosive and hostile constituents resulting in an exit temperature of 150°C, to generate an additional 4 MW. (See Table 1.) The use of the air cooled Integrated ORMAT® Combined Cycle technology has resulted in a power plant, which consumes no geothermal fluid or other water, makes effective use of a high enthalpy resource, with near zero environmental impact and has the ability to accommodate the changes in the resource anticipated in the future.

5. SUMMARY

The use of field proven binary based advanced power cycles has particular advantages for the commercialization of EGS/HDR technology. Case histories have demonstrated that:

- a wide range of geothermal fluid temperatures, have been effectively utilized;
- corrosive steam or geothermal brines may be utilized;
- no HDR/EGS produced water is consumed with 100% injection of all geothermal fluids;
- power plant operation is compatible with the pressures of HDR/EGS production facilities;
- the power plant may be matched to the resource to effectively optimize the initial resource condition, and allow for future changes in the water produced by the EGS;
- the overall project achieves a minimal environmental impact; and
- the power plant may be expanded as more EGS fluids are produced.

6. REFERENCES

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Table 1. Rotokawa Technical Specifications

Technical Specifications	
Geothermal Source Design Conditions	
Geothermal Steam and NCG Flow Rate	133.56 ton/hr (294,450 lb/hr)
Steam Dryness: Steam Pressure: Steam and Brine Temperature: Brine Flow Rate: Brine Outlet Temperature:	99.98% 23.24 bara (337 psia) 219°C (427°F) 304 ton/hr (670,206 lb/hr) 150°C (302°F)
Power Plant Performance at Design Point Conditions	
Power Produced - Gross: Power Produced - Net: Plant Voltage:	25.44 MW 23.44 MW 11 kV, 3-phase, 50 Hz
ORMAT® Combined Cycle Module (OCCM)	
Level I Back Pressure Steam Turbine	
Steam Turbine Type: Steam Outlet Pressure: Turbine/Generator Speed: Installed Capacity:	Multi-Stage Reaction 1.3 bara (18.9 psia) 3,000 rpm 15,000 kW
Level II Organic Rankine Cycle	
Organic Vapor Turbine Type: Turbine/Generator Speed: Total Installed Capacity:	2 Stage Impulse 1,500 rpm 10,000 kW
BRINE ORMAT® Energy Converter (OEC)	
Organic Vapor Turbine Type: Turbine/Generator Speed: Installed Capacity	2 Stage Impulse 1,500 rpm 5,000 kW

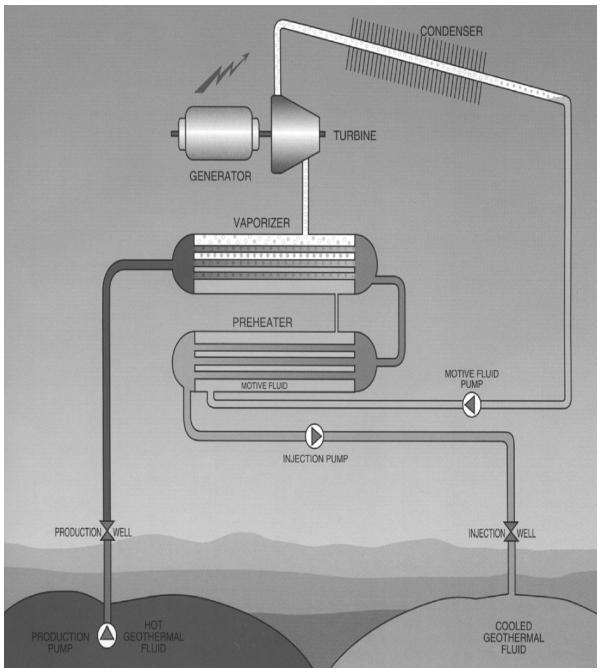


Figure 1. Process Diagram: Air Cooled Binary Geothermal Power Plant

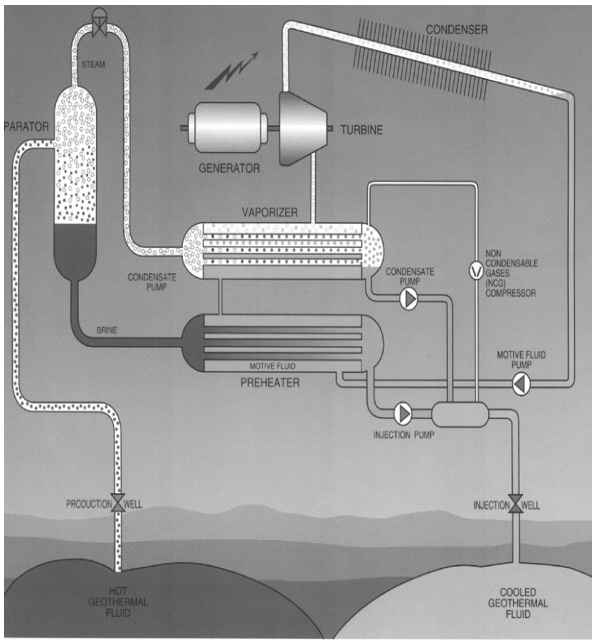


Figure 2. Process Diagram: Two-Phase Binary Geothermal Power Plant

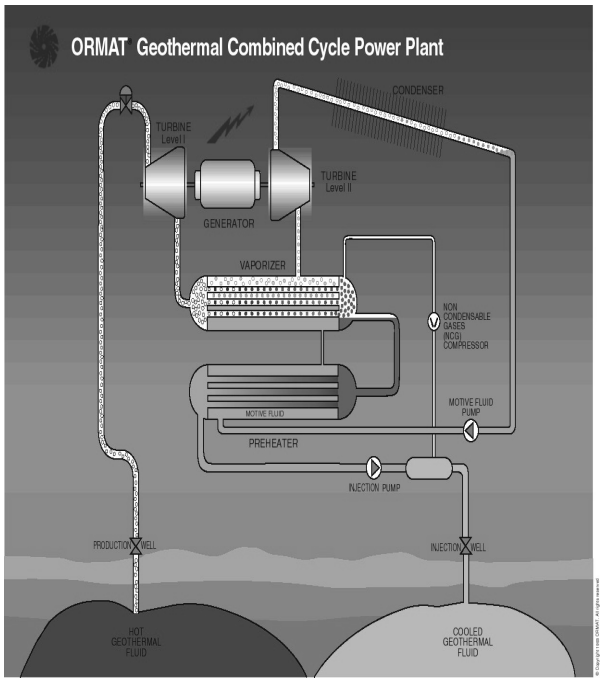


Figure 3. Process Diagram: ORMAT® Combined Cycle Unit

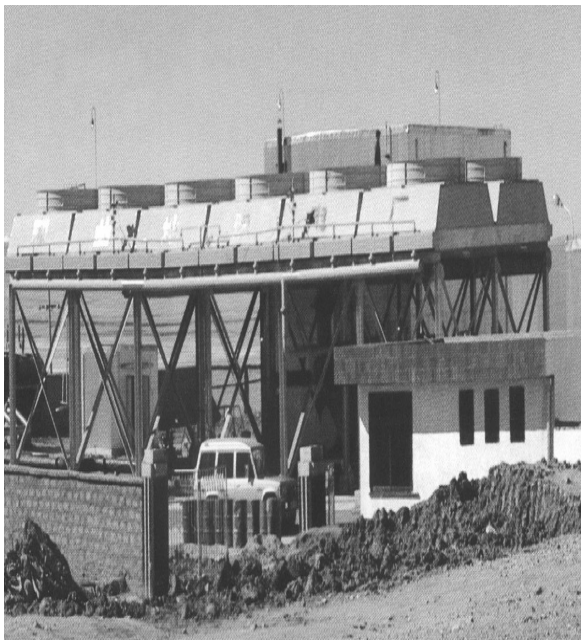


Figure 4. Nagqu 1.3 MW Air Cooled Binary Geothermal Plant

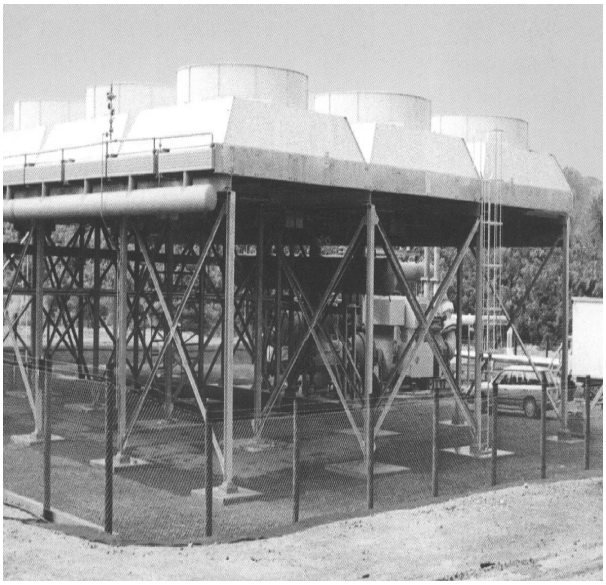


Figure 5. Kawerau 3.8 MW Air Cooled Binary Geothermal Plant

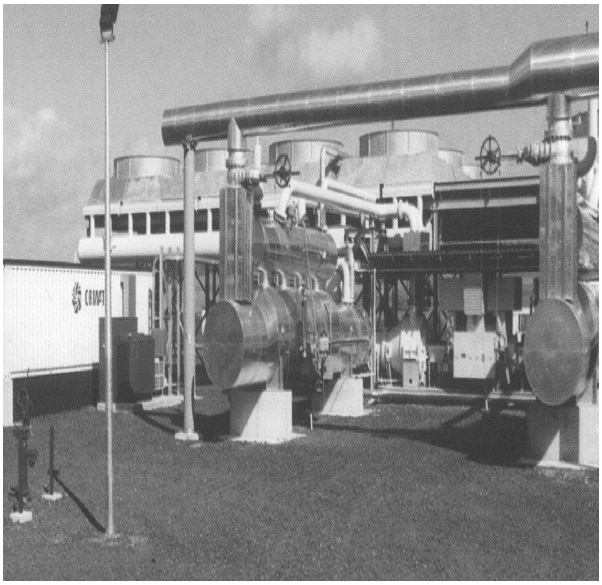


Figure 7. Rotokawa 27 MW Air Cooled Geothermal Combined Cycle Plant

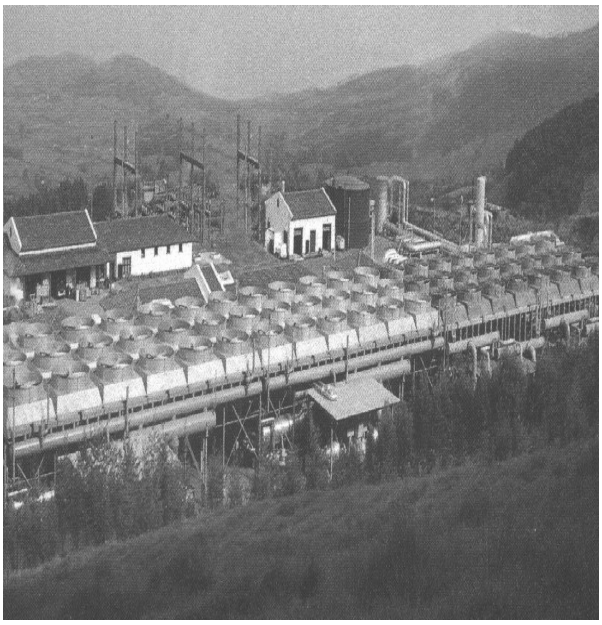


Figure 6. São Miguel 14 MW Air Cooled Binary Two Phase Geothermal Plant